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Patent Application

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A THERMAL ACTUATOR AND AN OPTICAL WAVEGUIDE SWITCH INCLUDING THE SAME

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CROSS-REFERENCE TO RELATED APPLICATION

This is a continuation-in-part of its commonly-assigned "parent" prior application number 10/634,941, filed 5 August 2003, now pending, attorney docket D/A3207, by Joel A. Kubby et al., the same inventors as in the present application, entitled "A thermal actuator and an optical waveguide switch including the same", the disclosure of which prior application is hereby incorporated by reference verbatim, with the same effect as though such disclosure were fully and completely set forth herein.

This application is related to the commonly-assigned application number _____ , filed on the same date as the present application, now pending, attorney docket D/A3207IQ, by Joel A. Kubby et al., the same inventors as in the present application, entitled "A thermal actuator with offset beam segment neutral axes and an optical waveguide switch including the same".

INCORPORATION BY REFERENCE OF OTHER PATENTS, PATENT APPLICATIONS AND PUBLICATIONS

The disclosures of the following thirteen (13) U.S. patents are hereby incorporated by reference, verbatim, and with the same effect as though the same disclosures were fully and completely set forth herein:

Joel Kubby, U.S. Pat. No. 5,706,041, "Thermal ink-jet printhead with a suspended heating element in each ejector," issued January 6, 1998;

Joel Kubby, U.S. Pat. No. 5,851,412, "Thermal ink-jet printhead with a suspended heating element in each ejector," issued December 22, 1998;

Joel Kubby et al., U.S. Pat. No. 6,362,512, "Microelectromechanical structures defined from silicon on insulator wafers," issued March 26, 2002;

Joel Kubby et al., U.S. Pat. No. 6,379,989, "Process for manufacture of microoptomechanical structures," issued April 30, 2002;

Phillip D. Floyd et al., U.S. Pat. No. 6,002,507, "Method and apparatus for an integrated laser beam scanner," issued December 14, 1999;

Phillip D. Floyd et al., U.S. Pat. No. 6,014,240, "Method and apparatus for an integrated laser beam scanner using a carrier substrate," issued January 11, 2000;

Robert L. Wood et al., U.S. Pat. No. 5,909,078, "Thermal arched beam microelectromechanical actuators," issued June 1, 1999;

Vijayakumar R. Dhuler et al., U.S. Pat. No. 5,994,816, "Thermal arched beam microelectromechanical devices and associated fabrication methods," issued November 30, 1999;

Vijayakumar R. Dhuler et al., U.S. Pat. No. 6,023,121, "Thermal arched beam microelectromechanical structure," issued February 8, 2000;

Vijayakumar R. Dhuler et al., U.S. Pat. No. 6,114,794, "Thermal arched beam microelectromechanical valve," issued September 5, 2000;

Vijayakumar R. Dhuler et al., U.S. Pat. No. 6,255,757, "Microactuators including a metal layer on distal portions of an arched beam," issued July 3, 2001;

Vijayakumar R. Dhuler et al., U.S. Pat. No. 6,324,748, "Method of fabricating a microelectro mechanical structure having an arched beam," issued December 4, 2001; and

Edward A. Hill et al., U.S. Pat. No. 6,360,539, "Microelectromechanical actuators including driven arched beams for mechanical advantage," issued March 26, 2002.

The disclosures of the following four (4) U.S. patent applications are hereby incorporated by reference, verbatim, and with the same effect as though the same disclosures were fully and completely set forth herein:

Joel Kubby, U.S. Pat. Application No. 09/683,533, "Systems and methods for thermal isolation of a silicon structure," filed January 16, 2002, now U.S. Patent Application Publication No. 20030134445, published July 17, 2003, attorney docket number D/A1129;

Joel Kubby, U.S. Pat. Application No. 60/456,086, "MxN Cantilever Beam Optical Waveguide Switch," filed March 19, 2003, attorney docket number D/A2415P;

Joel Kubby et al., U.S. Pat. Application No. 09/986,395, "Monolithic reconfigurable optical multiplexer systems and methods," filed November 8, 2001, now U.S. Patent Application Publication No. 20030086641, published May 8, 2003, attorney docket number D/A1063; and

Joel Kubby et al., U.S. Pat. Application No. 60/456,063, "MEMS Optical Latching Switch," filed March 19, 2003, attorney docket number D/A2415QP.

The disclosures of the following three (3) publications are hereby incorporated by reference, verbatim, and with the same effect as though the same disclosures were fully and completely set forth herein:

Yogesh B. Gianchandani and Khalil Najafi, "Bent-Beam Strain Sensors," Journal of Microelectromechanical Systems, Vol. 5, No.1, March 1996, pages 52-58;

Long Que, Jae-Sung Park and Yogesh B. Gianchandani, "Bent-Beam Electrothermal Actuators," Journal of Microelectromechanical Systems, Vol. 10, No. 2, June 2001, pages 247-254; and

John M. Maloney, Don L. DeVoe and David S. Schreiber, "Analysis and Design of Electrothermal Actuators Fabricated from Single Crystal Silicon," Proceedings ASME International Mechanical Engineering Conference and Exposition, Orlando, FL, pages 233-240, 2000.

FIELD OF THE INVENTION

This application relates generally to thermal actuators and more particularly to a thermal actuator that is suitable for use in an optical waveguide switch.

BACKGROUND OF THE INVENTION

The traditional thermal actuator, the "V-beam" actuator, is widely used in microelectromechanical or "MEMS" structures. Such actuators are described in U.S. Patent No. 5,909,078 to Robert L. Wood et al.; and in the U.S. Patents to Vijayakumar

R. Dhuler et al., Number 5,994,816, Number 6,023,121, Number 6,114,794, Number 6,255,757 and Number 6,324,748; and in U.S. Patent No. 6,360,539 to Edward A. Hill et al., all of the foregoing patents being incorporated by reference herein; and in the publication of Long Que, Jae-Sung Park and Yogesh B. Gianchandani, "Bent-Beam Electrothermal Actuators"; and in the publication of John M. Maloney, Don L. DeVoe and David S. Schreiber, "Analysis and Design of Electrothermal Actuators Fabricated from Single Crystal Silicon," both of which publications are incorporated by reference herein.

However, these actuators are sensitive to residual stresses, especially the stress introduced by doping during fabrication of the actuator.

Indeed, the bent-beam geometry used in these actuators has been used in bent-beam strain sensors to measure residual stress as described in the publication of Yogesh B. Gianchandani and Khalil Najafi, "Bent-Beam Strain Sensors," which publication is incorporated by reference herein.

The residual stress in the V-beam actuator acts to deflect the V-beams away from their originally-designed target locations since the beam angle gives rise to a transverse force. Moreover, when such a V-beam actuator is used in an optical waveguide switch, this residual stress results in waveguide misalignment. The amount of optical loss caused by this waveguide misalignment is substantial. As a result, currently the V-beam actuator is generally unacceptable for use in an optical waveguide switch.

Thus, there is a need for an actuator that is acceptable for use in an optical waveguide switch.

SUMMARY OF THE INVENTION

In a first aspect of the invention, a thermal actuator comprises a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a beam extending between the first support and the second support, the beam having a first side, a second side, a beam length and a beam mid-point, the beam being substantially straight along the first side; the beam comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment width orthogonal to the beam length, the beam thus

forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to the beam vary along the beam length based on a predetermined pattern; so that a heating of the beam causes a beam buckling and the beam mid-point to translate in a predetermined direction generally normal to and outward from the second side.

In a second aspect of the invention, a thermal actuator comprises a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a plurality of beams extending in parallel between the first support and the second support, thus forming a beam array; each beam of the beam array having a first side, a second side, a beam length and a beam mid-point, each beam being substantially straight along its first side; each beam of the beam array comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment width orthogonal to the beam length, each beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to each beam vary along the beam length based on a predetermined pattern; an included coupling beam extending orthogonally across the beam array to couple each beam of the beam array substantially at the corresponding beam mid-point; so that a heating of the beam array causes a beam array buckling and the coupling beam to translate in a predetermined direction generally normal to and outward from the second sides of the array beams.

In a third aspect of the invention, a thermal actuator comprises a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a beam extending between the first support and the second support, the beam having a first side, a second side, a beam length and a beam mid-point, the beam being substantially straight along the second side; the beam comprised of a plurality of beam segments, each beam segment of the plurality of beam segments being having a beam segment width orthogonal to the beam length, the beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to the beam vary along the beam length based on a predetermined pattern; so that a heating of the beam causes a

beam buckling and the beam mid-point to translate in a predetermined direction generally normal to and outward from the second side.

In a fourth aspect of the invention, a thermal actuator comprises a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a plurality of beams extending in parallel between the first support and the second support, thus forming a beam array; each beam of the beam array having a first side, a second side, a beam length and a beam mid-point, each beam being substantially straight along its second side; each beam of the beam array comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment width orthogonal to the beam length, each beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to each beam vary along the beam length based on a predetermined pattern; an included coupling beam extending orthogonally across the beam array to couple each beam of the beam array substantially at the corresponding beam mid-point; so that a heating of the beam array causes a beam array buckling and the coupling beam to translate in a predetermined direction generally normal to and outward from the second sides of the array beams.

In a fifth aspect of the invention, a thermal actuator comprises a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a beam extending between the first support and the second support, the beam having a first side, a second side, a beam length and a beam mid-point, the beam being substantially straight along the first side; the beam comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment average width orthogonal to the beam length, the beam thus forming a corresponding plurality of beam segment average widths; wherein the plurality of beam segment average widths corresponding to the beam vary along the beam length based on a predetermined pattern; so that a heating of the beam causes a beam buckling and the beam mid-point to translate in a predetermined direction generally normal to and outward from the second side.

In a sixth aspect of the invention, a thermal actuator comprises a substrate having a surface; a first support and a second support disposed on the

surface and extending orthogonally therefrom; a plurality of beams extending in parallel between the first support and the second support, thus forming a beam array; each beam of the beam array having a first side, a second side, a beam length and a beam mid-point, each beam being substantially straight along its first side; each beam of the beam array comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment average width orthogonal to the beam length, each beam thus forming a corresponding plurality of beam segment average widths; wherein the plurality of beam segment average widths corresponding to each beam vary along the beam length based on a predetermined pattern; an included coupling beam extending orthogonally across the beam array to couple each beam of the beam array substantially at the corresponding beam mid-point; so that a heating of the beam array causes a beam array buckling and the coupling beam to translate in a predetermined direction generally normal to and outward from the second sides of the array beams.

In a seventh aspect of the invention, an optical waveguide switch comprises a thermal actuator, the thermal actuator comprising a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a beam extending between the first support and the second support, the beam having a first side, a second side, a beam length and a beam mid-point, the beam being substantially straight along the first side; the beam comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment width orthogonal to the beam length, the beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to the beam vary along the beam length based on a predetermined pattern; so that a heating of the beam causes a beam buckling and the beam mid-point to translate in a predetermined direction generally normal to and outward from the second side.

In an eighth aspect of the invention, an optical waveguide switch comprises a thermal actuator, the thermal actuator comprising a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a plurality of beams extending in parallel between the first

support and the second support, thus forming a beam array; each beam of the beam array having a first side, a second side, a beam length and a beam mid-point, each beam being substantially straight along its first side; each beam of the beam array comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment width orthogonal to the beam length, each beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to each beam vary along the beam length based on a predetermined pattern; an included coupling beam extending orthogonally across the beam array to couple each beam of the beam array substantially at the corresponding beam mid-point; so that a heating of the beam array causes a beam array buckling and the coupling beam to translate in a predetermined direction generally normal to and outward from the second sides of the array beams.

In a ninth aspect of the invention, an optical waveguide switch comprises a thermal actuator, the thermal actuator comprising a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a beam extending between the first support and the second support, the beam having a first side, a second side, a beam length and a beam mid-point, the beam being substantially straight along the second side; the beam comprised of a plurality of beam segments, each beam segment of the plurality of beam segments being having a beam segment width orthogonal to the beam length, the beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to the beam vary along the beam length based on a predetermined pattern; so that a heating of the beam causes a beam buckling and the beam mid-point to translate in a predetermined direction generally normal to and outward from the second side.

In a tenth aspect of the invention, an optical waveguide switch comprises a thermal actuator, the thermal actuator comprising a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a plurality of beams extending in parallel between the first support and the second support, thus forming a beam array; each beam of the beam array having a first side, a second side, a beam length and a beam mid-point, each beam being

substantially straight along its second side; each beam of the beam array comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment width orthogonal to the beam length, each beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths corresponding to each beam vary along the beam length based on a predetermined pattern; an included coupling beam extending orthogonally across the beam array to couple each beam of the beam array substantially at the corresponding beam mid-point; so that a heating of the beam array causes a beam array buckling and the coupling beam to translate in a predetermined direction generally normal to and outward from the second sides of the array beams.

In an eleventh aspect of the invention, an optical waveguide switch comprises a thermal actuator, the thermal actuator comprising a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a beam extending between the first support and the second support, the beam having a first side, a second side, a beam length and a beam mid-point, the beam being substantially straight along the first side; the beam comprised of a plurality of beam segments, each beam segment of the plurality of beam segments having a beam segment average width orthogonal to the beam length, the beam thus forming a corresponding plurality of beam segment average widths; wherein the plurality of beam segment average widths corresponding to the beam vary along the beam length based on a predetermined pattern; so that a heating of the beam causes a beam buckling and the beam mid-point to translate in a predetermined direction generally normal to and outward from the second side.

In a twelfth aspect of the invention, an optical waveguide switch comprises a thermal actuator, the thermal actuator comprising a substrate having a surface; a first support and a second support disposed on the surface and extending orthogonally therefrom; a plurality of beams extending in parallel between the first support and the second support, thus forming a beam array; each beam of the beam array having a first side, a second side, a beam length and a beam mid-point, each beam being substantially straight along its first side; each beam of the beam array comprised of a plurality of beam segments, each beam segment of the plurality of beam

segments having a beam segment average width orthogonal to the beam length, each beam thus forming a corresponding plurality of beam segment average widths; wherein the plurality of beam segment average widths corresponding to each beam vary along the beam length based on a predetermined pattern; an included coupling beam extending orthogonally across the beam array to couple each beam of the beam array substantially at the corresponding beam mid-point; so that a heating of the beam array causes a beam array buckling and the coupling beam to translate in a predetermined direction generally normal to and outward from the second sides of the array beams.

BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWING

FIG. 1 is a block diagram of an optical waveguide switch 100a comprising a first embodiment 200 of a thermal actuator.

FIG. 2 is a block diagram of an optical waveguide switch 100b comprising a second embodiment 300 of thermal actuator.

FIG. 3 is a block diagram of an optical waveguide switch 100c comprising a third embodiment 400 of a thermal actuator.

FIGS. 4-6 depict the first embodiment 200 of the thermal actuator as follows:

FIG. 4 is an elevated top-down "birds-eye" view of the thermal actuator 200, including a first reference line 5 and a second reference line 6.

FIG. 5 is a first "cut-away" side or profile view of the thermal actuator 200 along the FIG. 4 first reference line 5.

FIG. 6 is a second "cut-away" side or profile view of the thermal actuator 200 along the FIG. 4 second reference line 6.

FIGS. 7-9 depict the second embodiment 300 of the thermal actuator as follows:

FIG. 7 is an elevated top-down "birds-eye" view of the thermal actuator 300, including a first reference line 8 and a second reference line 9.

FIG. 8 is a first "cut-away" side or profile view of the thermal actuator 300 along the FIG. 7 first reference line 8.

FIG. 9 is a second "cut-away" side or profile view of the thermal actuator 300 along the FIG. 7 second reference line 9.

FIGS. 10-12 depict the third embodiment 400 of the thermal actuator as follows:

FIG. 10 is an elevated top-down "birds-eye" view of the thermal actuator 400, including a first reference line 11 and a second reference line 12.

FIG. 11 is a first "cut-away" side or profile view of the thermal actuator 400 along the FIG. 10 first reference line 11.

FIG. 12 is a second "cut-away" side or profile view of the thermal actuator 400 along the FIG. 10 second reference line 12.

FIG. 13 is a block diagram of an optical waveguide switch 100d comprising a fourth embodiment 500 of a thermal actuator.

FIG. 14 is a block diagram of an optical waveguide switch 100e comprising a fifth embodiment 600 of thermal actuator.

FIG. 15 is a block diagram of an optical waveguide switch 100f comprising a sixth embodiment 700 of a thermal actuator.

FIG. 16 is a block diagram of an optical waveguide switch 100g comprising a seventh embodiment 800 of a thermal actuator.

FIG. 17 is a block diagram of an optical waveguide switch 100h comprising an eighth embodiment 900 of thermal actuator.

FIG. 18 is a block diagram of an optical waveguide switch 100i comprising a ninth embodiment 1000 of a thermal actuator.

FIG. 19 is an elevated top-down "birds-eye" view of the fourth embodiment 500 of the thermal actuator, including reference lines 20-24.

FIG. 20 is a "cut-away" side or profile view of the thermal actuator 500 along the reference line 20.

FIG. 21 is a "cut-away" side or profile view of the thermal actuator 500 along the reference line 21.

FIG. 22 is a "cut-away" side or profile view of the thermal actuator 500 along the reference line 22.

FIG. 23 is a "cut-away" side or profile view of the thermal actuator 500 along the reference line 23.

FIG. 24 is a "cut-away" side or profile view of the thermal actuator 500 along the reference line 24.

FIG. 25 is an elevated top-down "birds-eye" view of the fifth embodiment 600 of the thermal actuator, including reference lines 26-30.

FIG. 26 is a "cut-away" side or profile view of the thermal actuator 600 along the reference line 26.

FIG. 27 is a "cut-away" side or profile view of the thermal actuator 600 along the reference line 27.

FIG. 28 is a "cut-away" side or profile view of the thermal actuator 600 along the reference line 28.

FIG. 29 is a "cut-away" side or profile view of the thermal actuator 600 along the reference line 29.

FIG. 30 is a "cut-away" side or profile view of the thermal actuator 600 along the reference line 30.

FIG. 31 is an elevated top-down "birds-eye" view of the sixth embodiment 700 of the thermal actuator, including reference lines 32-36.

FIG. 32 is a "cut-away" side or profile view of the thermal actuator 700 along the reference line 32.

FIG. 33 is a "cut-away" side or profile view of the thermal actuator 700 along the reference line 33.

FIG. 34 is a "cut-away" side or profile view of the thermal actuator 700 along the reference line 34.

FIG. 35 is a "cut-away" side or profile view of the thermal actuator 700 along the reference line 35.

FIG. 36 is a "cut-away" side or profile view of the thermal actuator 700 along the reference line 36.

FIG. 37 is an elevated top-down "birds-eye" view of the seventh embodiment 800 of the thermal actuator, including reference lines 38-42.

FIG. 38 is a "cut-away" side or profile view of the thermal actuator 800 along the reference line 38.

FIG. 39 is a "cut-away" side or profile view of the thermal actuator 800 along the reference line 39.

FIG. 40 is a "cut-away" side or profile view of the thermal actuator 800 along the reference line 40.

FIG. 41 is a "cut-away" side or profile view of the thermal actuator 800 along the reference line 41.

FIG. 42 is a "cut-away" side or profile view of the thermal actuator 800 along the reference line 42.

FIG. 43 is an elevated top-down "birds-eye" view of then eighth embodiment 900 of the thermal actuator, including reference lines 44-48.

FIG. 44 is a "cut-away" side or profile view of the thermal actuator 900 along the reference line 44.

FIG. 45 is a "cut-away" side or profile view of the thermal actuator 900 along the reference line 45.

FIG. 46 is a "cut-away" side or profile view of the thermal actuator 900 along the reference line 46.

FIG. 47 is a "cut-away" side or profile view of the thermal actuator 900 along the reference line 47.

FIG. 48 is a "cut-away" side or profile view of the thermal actuator 900 along the reference line 48.

FIG. 49 is an elevated top-down "birds-eye" view of the ninth embodiment 1000 of the thermal actuator 1000, including reference lines 50-54.

FIG. 50 is a "cut-away" side or profile view of the thermal actuator 1000 along the reference line 50.

FIG. 51 is a "cut-away" side or profile view of the thermal actuator 1000 along the reference line 51.

FIG. 52 is a "cut-away" side or profile view of the thermal actuator 1000 along the reference line 52.

FIG. 53 is a "cut-away" side or profile view of the thermal actuator 1000 along the reference line 53.

FIG. 54 is a "cut-away" side or profile view of the thermal actuator 1000 along the reference line 54.

DETAILED DESCRIPTION OF THE INVENTION

Referring now to the optical waveguide switches 100a, 100b, 100c and their corresponding thermal actuators 200, 300, 400 described below in connection with FIGS. 1-12, in brief, a thermal actuator 200, 300 or 400 comprises a plurality of substantially straight and parallel beams arranged to form a beam array. The mid-point of each beam is attached or coupled to an orthogonal coupling beam. Each array beam has a beam heating parameter with a corresponding beam heating parameter value. The beam heating parameter values vary across the beam array based on a predetermined pattern. As the beams are heated by an included heating means, the distribution of beam temperatures in the beam array becomes asymmetric, thus causing the beam array to buckle. The buckling of the beams in the beam array, in turn, causes the attached coupling beam to translate or move in a predetermined direction. The coupling beam movement, in turn, operates an included optical waveguide switch 100a, 100b or 100c. The beams in the beam array are heated by any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring now to the optical waveguide switches 100d and 100f and their corresponding thermal actuators 500 and 700 described below in connection with FIGS. 13, 15, 19-24 and 31-36, in brief, a thermal actuator 500 or 700 comprises a substantially straight beam 510 or 710. The beam has a beam length 518 or 718 and a beam mid-point 519 or 719. The beam comprises a plurality of beam segments 520, 522, 524 or 720, 722, 724 with corresponding beam segment widths 525, 526, 527 or 725, 726, 727. The beam segment widths vary along the beam length based on a predetermined pattern. As the beam is heated by an included heating means, the beam buckles. The buckling of the beam, in turn, causes the beam mid-point to translate or move in a predetermined direction 548 or 748. The beam mid-point movement, in turn, operates an included optical waveguide switch 100d or 100f. The heating means comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring now to the optical waveguide switches 100e and 100g and their corresponding thermal actuators 600 and 800 described below in connection with FIGS. 14, 16, 25-30 and 37-42, in brief, a thermal actuator 600 or 800 comprises a plurality of beams 610a, 610b, 610c or 810a, 810b, 810c, each beam substantially similar to the beam 510 or 710 described above, the plurality of beams arranged to form a beam array 613 or 813. The mid-point of each beam is attached or coupled to an orthogonal coupling beam 614 or 814. As the plurality of beams are heated by an included heating means, the beam array buckles. The buckling of the beams in the beam array, in turn, causes the attached coupling beam to more in a predetermined direction 648 or 848. The coupling beam movement, in turn, operates an included optical waveguide switch 100e or 100g. The heating means comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring now to the optical waveguide switch 100h and its corresponding thermal actuator 900 described below in connection with FIGS. 17 and 43-48, in brief, a thermal actuator 900 comprises a substantially straight beam 910. The beam has a beam length 918 and a beam mid-point 919. The beam comprises a plurality of beam segments 920, 921, 922, 923, 924 with beam segment lengths. Each beam segment has a beam segment average width, thus forming a corresponding plurality of beam segment average widths 925, 931, 926, 933, 927. The beam segment average widths vary along the beam length based on a predetermined pattern. As the beam is heated by an included heating means, the beam buckles. The buckling of the beam, in turn, causes the beam mid-point to translate or move in a predetermined direction 948. The beam mid-point movement, in turn, operates an included optical waveguide switch 100h. The heating means comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring now to the optical waveguide switch 100i and its corresponding thermal actuator 1000 described below in connection with FIGS. 18 and 49-54, in brief, a thermal actuator 1000 comprises a plurality of beams 1010a, 1010b, 1010c, the plurality of beams arranged to form a beam array 1009. Each beam comprises a plurality of beam segments 1020, 1021, 1022, 1023, 1024. Each beam segment has a

beam segment average width, the plurality of beams thus forming a corresponding plurality of beam segment average widths 1025a, 1031a, 1026a, 1033a, 1027a; 1025b, 1031b, 1026b, 1033b, 1027b; 1025c, 1031c, 1026c, 1033c, 1027c. The plurality of beam segment average widths corresponding to each beam vary along the beam length based on a predetermined pattern. The mid-point 1019 of each beam is attached or coupled to an orthogonal coupling beam 1005. As the plurality of beams are heated by an included heating means, the beam array buckles. The buckling of the beams in the beam array, in turn, causes the attached coupling beam to more in a predetermined direction 1048. The coupling beam movement, in turn, operates an included optical waveguide switch 100i. The heating means comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring now to FIG. 1, there is shown a block diagram of an optical waveguide switch 100a comprising a first embodiment 200 of a thermal actuator. The thermal actuator 200 is described in greater detail in connection with FIGS. 4-6 below.

Referring now to FIG. 2, there is shown a block diagram of an optical waveguide switch 100b comprising a second embodiment 300 of thermal actuator. The thermal actuator 300 is described in greater detail in connection with FIGS. 7-9 below.

Referring now to FIG. 3, there is shown a block diagram of an optical waveguide switch 100c comprising a third embodiment 400 of a thermal actuator. The thermal actuator 400 is described in greater detail in connection with FIGS. 10-12 below.

Examples of optical waveguide switches that incorporate thermal actuators have been described in the application of Joel Kubby, U.S. Pat. Application No. 60/456,086, filed March 19, 2003; and in the applications of Joel Kubby et al., U.S. Pat. Application No. 09/986,395, filed November 8, 2001, now U.S. Patent Application Publication No. 20030086641, published May 8, 2003; and U.S. Pat. Application No. 60/456,063, filed March 19, 2003, all of the foregoing patent applications being incorporated by reference herein.

FIGS. 4-6 depict the thermal actuator 200 in greater detail.

Referring now to FIG. 4, there is shown an elevated top-down "birds-eye" view of the thermal actuator 200, including a first reference line 5 and a second reference line 6. As shown, the thermal actuator 200 comprises a substrate 202 having a surface 204; a first support 206 and a second support 208 disposed on the surface and extending orthogonally therefrom, a plurality of beams 212a - 212d extending in parallel between the first support and the second support, thus forming a beam array 214, each beam being agonic and substantially straight; each beam of the beam array having a beam width 226 with a corresponding beam width value, the beams in the beam array having beam width values that vary based on a predetermined pattern; and an included coupling beam 220 extending orthogonally across the beam array to couple each array beam substantially at its mid-point.

The predetermined pattern is characterized in that, across the beam array 214 from one side 250 of the beam array to the opposite side 252 of the beam array, successive beam width values do not decrease and at least sometimes increase.

Each pair 222 of adjacent beams in the beam array 214 has a beam spacing 224 with a corresponding beam spacing value, with all such pairs of adjacent beams in the beam array having substantially the same beam spacing value.

As shown in FIG. 4, with cross-reference to FIGS. 5-6, in one embodiment, the thermal actuator 200 includes a heater layer 228 disposed on the surface facing the plurality of beams and arranged to heat the plurality of beams. The heater layer is coupled to a heater layer input 238 and a heater layer output 240 and arranged to cause or form a heating of the plurality of beams.

The heater layer 228 can be thermally isolated from the substrate as described in U.S. Patents Number 5,706,041 and Number 5,851,412 to Joel Kubby, both of which patents are incorporated by reference herein.

Further, in one embodiment, each beam of the plurality of beams is arranged to be heated by a beam heater current 246 supplied by an included beam input 242 and beam output 244, thus resulting in a heating of the plurality of beams.

The plurality of beams can be thermally isolated from the substrate as described in the application of Joel Kubby, U.S. Pat. Application No. 09/683,533, filed

January 16, 2002, now U.S. Patent Application Publication No. 20030134445, published July 17, 2003, which patent application is incorporated by reference herein.

As shown, the plurality of beams is arranged so that the heating of the plurality of beams causes a beam buckling and the coupling beam to translate in a predetermined direction 248. In one embodiment, the heating of the plurality of beams is supplied by the heater layer 228. In another embodiment, the heating of the plurality of beams is supplied by the beam heater current 246. In still another embodiment, the heating of the plurality of beams is supplied by a combination of the heater layer 228 and the beam heater current 246.

Referring generally to FIGS. 4-6, in one embodiment, each beam of the plurality of beams is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In one embodiment, each beam of the plurality of beams is fabricated in a device layer 230 of a silicon-on-insulator wafer 232.

A method for fabricating the plurality of beams in a device layer of a silicon-on-insulator wafer is described in the U.S. Patents to Phillip D. Floyd et al., Number 6,002,507 and Number 6,014,240; and in the U.S. Patents to Joel Kubby et al., Number 6,362,512 and Number 6,379,989, all of the foregoing patents being incorporated by reference herein.

In one embodiment, the first support 206 and second support 208 are fabricated in a buried oxide layer 234 of a silicon-on-insulator wafer 232.

FIGS. 7-9 depict the thermal actuator 300 in greater detail.

Referring now to FIG. 7, there is shown an elevated top-down "birds-eye" view of the thermal actuator 300, including a first reference line 8 and a second reference line 9. As shown, the thermal actuator 300 comprises a substrate 302 having a surface 304; a first support 306 and a second support 308 disposed on the surface and extending orthogonally therefrom, a plurality of beams extending in parallel between the first support and the second support, thus forming a beam array 314, each beam being agonic and substantially straight; each pair 322 of adjacent beams in the beam array defining a beam spacing with a corresponding beam spacing value, the pairs of adjacent beams in the beam array having beam spacing values that vary based

on a predetermined pattern; and an included coupling beam 320 extending orthogonally across the beam array to couple each array beam substantially at its mid-point.

The predetermined pattern is characterized in that, across the beam array 314 from one side 350 of the beam array to the opposite side 352 of the beam array, successive beam spacing values do not decrease and at least sometimes increase.

Each beam of the beam array 314 has a beam width 326 with a corresponding beam width value, with all beams of the beam array having substantially the same beam width value.

As shown in FIG. 7, with cross-reference to FIGS. 8-9, in one embodiment, the thermal actuator 300 includes a heater layer 328 disposed on the surface facing the plurality of beams and arranged to heat the plurality of beams. The heater layer is coupled to a heater layer input 338 and a heater layer output 340, and is arranged to cause or form a heating of the plurality of beams.

Further, in one embodiment, each beam of the plurality of beams is arranged to be heated by a beam heater current 346 supplied by an included beam input 342 and beam output 344, thus resulting in a heating of the plurality of beams.

As shown, the plurality of beams is arranged so that the heating of the plurality of beams causes a beam buckling and the coupling beam to translate in a predetermined direction 348. In one embodiment, the heating of the plurality of beams is supplied by the heater layer 328. In another embodiment, the heating of the plurality of beams is supplied by the beam heater current 346. In still another embodiment, the heating of the plurality of beams is supplied by a combination of the heater layer 328 and the beam heater current 346.

Referring generally to FIGS. 7-9, in one embodiment, each beam of the plurality of beams is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In one embodiment, each beam of the plurality of beams is fabricated in a device layer 330 of a silicon-on-insulator wafer 332.

In one embodiment, the first support 306 and the second support 308 are fabricated in a buried oxide layer 334 of a silicon-on-insulator wafer 332.

FIGS. 10-12 depict the thermal actuator 400 in greater detail.

Referring now to FIG. 10, there is shown an elevated top-down "birds-eye" view of the thermal actuator 400, including a first reference line 11 and a second reference line 12. As shown, the thermal actuator 400 comprises a substrate 402 having a surface 404; a first support 406 and a second support 408 disposed on the surface and extending orthogonally therefrom, a plurality of beams 412a - 412e extending in parallel between the first support and the second support, thus forming a beam array 414, each beam being agonic and substantially straight; each beam of the beam array having a beam resistance 436 with a corresponding beam resistance value, the beams in the beam array having beam resistance values that vary based on a predetermined pattern; and an included coupling beam 420 extending orthogonally across the beam array to couple each array beam substantially at its mid-point.

The predetermined pattern is characterized in that, across the beam array 414 from one side 450 of the beam array to the opposite side 452 of the beam array, successive beam resistance values do not increase and at least sometimes decrease.

Each beam of the beam array 414 has a beam width 426 with a corresponding beam width value, with all beams of the beam array having substantially the same beam width value.

Each pair 422 of adjacent beams in the beam array 414 defines a beam spacing 424 with a corresponding beam spacing value, with all such pairs of adjacent beams in the beam array having substantially the same beam spacing value.

As shown in FIG. 10, with cross-reference to FIGS. 11-12, in one embodiment, each beam of the plurality of beams is arranged to be heated by a beam heater current 446 supplied by an included beam input 442 and beam output 444, thus causing or forming a heating of the plurality of beams.

As shown, the plurality of beams is arranged so that the heating of the plurality of beams causes a beam buckling and the coupling beam to translate in a predetermined direction 448.

Referring generally to FIGS. 10-12, in one embodiment, the thermal actuator 400 comprises a microelectromechanical or "MEMS" structure that is fabricated by any of surface and bulk micromachining.

In one embodiment, each beam of the plurality of beams is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In one embodiment, each beam of the plurality of beams is fabricated in a device layer 430 of a silicon-on-insulator wafer 432.

In one embodiment, the first support 406 and the second support 408 are fabricated in a buried oxide layer 434 of a silicon-on-insulator wafer 432.

Referring again to FIGS. 4-6, there is described below a further aspect of the thermal actuator 200.

In FIGS. 4-6 there is shown the thermal actuator 200 comprising a substrate 202 having a surface 204; a first support 206 and a second support 208 disposed on the surface and extending orthogonally therefrom, a plurality of beams 212a - 212d extending in parallel between the first support and the second support, thus forming a beam array 214, each beam being agonic and substantially straight; each beam of the beam array having a beam heating parameter 254 with a corresponding beam heating parameter value, the beams in the beam array having beam heating parameter values that vary based on a predetermined pattern; and an included coupling beam 220 extending orthogonally across the beam array to couple each array beam substantially at its mid-point.

An example of a beam heating parameter 254 is the beam width 226. The beam width w will effect the heat flow $\partial Q/\partial t$ through the beam under a temperature gradient $\partial T/\partial x$ as determined by Fourier's law of heat conduction in one dimension;

$$\partial Q/\partial t = \lambda(T)A\partial T/\partial x \,;$$

where the beam cross-section area A is given by the product of the beam width w and the beam thickness t;

$$A = (w)(t);$$

and $\lambda(T)$ is the temperature-dependent thermal conductivity of the beam. The beam width w will also effect the heat capacity of the beam, and thus the temperature of the beam as a function of time for a given heat input Q as given in one dimension by the heat equation;

$$\rho C\partial T/\partial t - \lambda(T)\partial T^2/\partial x^2 = Q + h(T_{ext} - T)$$

where ρ is the density of the beam, C is the heat capacity of the beam, h is the convective heat transfer coefficient, and T_{ext} is the external temperature. For a given beam thickness t, a wider beam width w will increase the heat capacity of the beam, and thus decrease the temperature the beam will reach after a certain amount of time for a given heat input Q.

A further example of a beam heating parameter 254 is the beam spacing 224. Heat can be transferred between beams by conduction, convection and radiation. The smaller the beam spacing, the greater the heat transfer between beams. Heat lost by one beam can be transferred to a nearby beam, and vice-versa. Heat can also be lost from beams by conduction, convection and radiation to the surrounding environment. The larger the beam spacing, the greater the heat loss from a beam to the surrounding environment.

A final example of a beam heating parameter 254 is the beam electrical resistance R. The beam resistance R will effect the amount of heat Q generated by a current I flowing through a beam with a resistance R for a time t by;

$$Q = I^2Rt$$

as given by Joule's law.

Each beam of the beam array 214 is characterized by an average beam temperature 236a - 236d, the average beam temperatures of the array beams thus forming an average beam temperature distribution 256. Further, there is provided heating means to heat each beam of the plurality of beams, thus causing or forming a heating of the plurality of beams. The heating means includes any of direct current Joule heating, by passing a beam heater current such as, for example, the beam current 246 through each beam, and indirect heating by conduction, convection or radiation from a heater layer such as, for example, the heater layer 228 disposed on the substrate, by passing a heater current through the heater layer. Further, in embodiments using a heater layer, the heater layer can be thermally isolated from the substrate as described in U.S. Patents Number 5,706,041 and Number 5,851,412 to Joel Kubby, and in U.S. Patent Number 6,362,512 to Joel Kubby et al., all of which patents are incorporated by reference herein.

The predetermined pattern is characterized in that, across the beam array 214 from one side 250 of the beam array to the opposite side 252 of the beam array, successive beam heating parameter values are arranged so that the beam temperature distribution becomes asymmetric based on the heating of the plurality of beams.

As shown, the plurality of beams is arranged so that the heating of the plurality of beams causes a beam buckling and the coupling beam 220 to translate in a predetermined direction 248.

Further heating of the plurality of the beams causes further expansion of the beams, thus causing the coupling beam to further translate in the predetermined direction 248.

In one embodiment, the heating of the plurality of beams comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring again to FIGS. 7-9, there is described below a further aspect of the thermal actuator 300.

In FIGS. 7-9 there is shown the thermal actuator 300 comprising a substrate 302 having a surface 304; a first support 306 and a second support 308 disposed on the surface and extending orthogonally therefrom, a plurality of beams 312a - 312e extending in parallel between the first support and the second support, thus forming a beam array 314, each beam being agonic and substantially straight; each beam of the beam array having a beam heating parameter 354 with a corresponding beam heating parameter value, the beams in the beam array having beam heating parameter values that vary based on a predetermined pattern; and an included coupling beam 320 extending orthogonally across the beam array to couple each array beam substantially at its mid-point.

Each beam of the beam array 314 is characterized by an average beam temperature, the average beam temperatures of the array beams thus forming an average beam temperature distribution. Further, there is provided heating means to heat each beam of the plurality of beams, thus causing or forming a heating of the plurality of beams. The heating means includes any of direct current Joule heating, by passing a beam heater current such as, for example, the beam current 346 through

each beam, and indirect heating by conduction, convection or radiation from a heater layer such as, for example, the heater layer 328 disposed on the substrate, by passing a heater current through the heater layer. Further, in embodiments using a heater layer, the heater layer can be thermally isolated from the substrate as described in U.S. Patents Number 5,706,041 and Number 5,851,412 to Joel Kubby, and in U.S. Patent Number 6,362,512 to Joel Kubby et al., all of which patents are incorporated by reference herein.

The predetermined pattern is characterized in that, across the beam array 314 from one side 350 of the beam array to the opposite side 352 of the beam array, successive beam heating parameter values are arranged so that the beam temperature distribution becomes asymmetric based on the heating of the plurality of beams.

As shown, the plurality of beams is arranged so that the heating of the plurality of beams causes a beam buckling and the coupling beam 320 to translate in a predetermined direction 348.

In one embodiment, the heating of the plurality of beams comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring again to FIGS. 10-12, there is described below a further aspect of the thermal actuator 400.

In FIGS. 10-12 there is shown the thermal actuator 400 comprising a substrate 402 having a surface 404; a first support 406 and a second support 408 disposed on the surface and extending orthogonally therefrom, a plurality of beams 412a - 412e extending in parallel between the first support and the second support, thus forming a beam array 414, each beam being agonic and substantially straight; each beam of the beam array having a beam heating parameter 454 with a corresponding beam heating parameter value, the beams in the beam array having beam heating parameter values that vary based on a predetermined pattern; and an included coupling beam 420 extending orthogonally across the beam array to couple each array beam substantially at its mid-point.

Each beam of the beam array 414 is characterized by an average beam temperature, the average beam temperatures of the array beams thus forming an

average beam temperature distribution. Further, there is provided heating means to heat each beam of the plurality of beams, thus causing or forming a heating of the plurality of beams. The heating means includes any of direct current Joule heating, by passing a beam heater current such as, for example, the beam current 446 through each beam, and indirect heating by conduction, convection or radiation from a heater layer such as, for example, the heater layer 428 disposed on the substrate, by passing a heater current through the heater layer. Further, in embodiments using a heater layer, the heater layer can be thermally isolated from the substrate as described in U.S. Patents Number 5,706,041 and Number 5,851,412 to Joel Kubby, and in U.S. Patent Number 6,362,512 to Joel Kubby et al., all of which patents are incorporated by reference herein.

The predetermined pattern is characterized in that, across the beam array 414 from one side 450 of the beam array to the opposite side 452 of the beam array, successive beam heating parameter values are arranged so that the beam temperature distribution becomes asymmetric based on the heating of the plurality of beams.

As shown, the plurality of beams is arranged so that the heating of the plurality of beams causes a beam buckling and the coupling beam 420 to translate in a predetermined direction 448.

In one embodiment, the heating of the plurality of beams comprises any of Joule heating, eddy current heating, conduction heating, convection heating and radiation heating.

Referring now to FIG. 13, there is shown a block diagram of an optical waveguide switch 100d comprising a fourth embodiment 500 of a thermal actuator. The thermal actuator 500 is described in greater detail in connection with FIGS. 19-24 below.

Referring now to FIG. 14, there is shown a block diagram of an optical waveguide switch 100e comprising a fifth embodiment 600 of a thermal actuator. The thermal actuator 600 is described in greater detail in connection with FIGS. 25-30 below.

Referring now to FIG. 15, there is shown a block diagram of an optical waveguide switch 100f comprising a sixth embodiment 700 of a thermal actuator. The

thermal actuator 700 is described in greater detail in connection with FIGS. 31-36 below.

Referring now to FIG. 16, there is shown a block diagram of an optical waveguide switch 100g comprising a seventh embodiment 800 of a thermal actuator. The thermal actuator 800 is described in greater detail in connection with FIGS. 37-42 below.

Referring now to FIG. 17, there is shown a block diagram of an optical waveguide switch 100h comprising an eighth embodiment 900 of a thermal actuator. The thermal actuator 900 is described in greater detail in connection with FIGS. 43-48 below.

Referring now to FIG. 18, there is shown a block diagram of an optical waveguide switch 100i comprising a ninth embodiment 1000 of a thermal actuator. The thermal actuator 1000 is described in greater detail in connection with FIGS. 49-54 below.

FIGS. 19-24 depict the thermal actuator 500 in greater detail.

Referring now to FIG. 19, there is shown an elevated top-down "birds-eye" view of the thermal actuator 500, including five (5) reference lines numbered 20-24.

As shown in FIGS. 19-24, the thermal actuator 500 comprises a substrate 502 having a surface 504; a first support 506 and a second support 508 disposed on the surface 504 and extending orthogonally therefrom; a beam 510 extending between the first support 506 and the second support 508, the beam 510 having a first side 511, a second side 512, a beam length 518 and a beam mid-point 519, the beam 510 being substantially straight along the first side 511; the beam comprised of a plurality of beam segments 520, 522, 524, each beam segment of the plurality of beam segments having a beam segment width 525, 526, 527 orthogonal to the beam length 518, the beam 510 thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths 525, 526, 527 corresponding to the beam 510 vary along the beam length 518 based on a predetermined pattern; so that a heating of the beam 510 causes a beam buckling and the beam mid-point 519 to translate in a predetermined direction 548 generally normal to and outward from the second side 512.

As shown in FIG. 19, in one embodiment, the predetermined pattern is characterized in that, along the beam length 518 from the first support 506 to the beam mid-point 519, beam segment widths 525, 526 corresponding to successive beam segments 520, 522 do not decrease and at least sometimes increase, and along the beam length 518 from the beam mid-point 519 to the second support 508, beam segment widths 526, 527 corresponding to successive beam segments 522, 524 do not increase and at least sometimes decrease.

In one embodiment, the heating of the beam 510 is provided by an included heater layer 528 disposed on the surface 504, the heater layer coupled to a heater layer input 538 and a heater layer output 540.

In another embodiment, the heating of the beam 510 is provided by a beam heater current 546 supplied by an included beam input 542 and beam output 544.

In one embodiment, the beam is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In another embodiment, the beam is fabricated in a device layer of a silicon-on-insulator wafer.

As shown in FIG. 19, in one embodiment, the beam 510 comprises exactly three (3) beam segments 520, 522, 524.

In another embodiment, the beam 510 comprises a plurality (n) of beam segments, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

As shown in FIG. 19, in one embodiment, the beam 510 comprises exclusively beam segments 520, 522, 524 having substantially parallel sides.

As further shown in FIG. 19, in one embodiment, the beam 510 comprises exactly two (2) beam segments 520, 524 that are substantially equal with respect to their corresponding beam segment lengths and beam segment widths 525, 527.

FIGS. 25-30 depict the thermal actuator 600 in greater detail.

Referring now to FIG. 25, there is shown an elevated top-down "birds-eye" view of the thermal actuator 600, including five (5) reference lines numbered 26-30.

As shown in FIGS. 25-30, the thermal actuator 600 comprises a substrate 602 having a surface 604; a first support 606 and a second support 608 disposed on the surface 604 and extending orthogonally therefrom; a plurality of beams 610a, 610b, 610c extending in parallel between the first support 606 and the second support 608, thus forming a beam array 613; each beam 610a, 610b, 610c of the beam array 613 having a first side 611a, 611b, 611c, a second side 612a, 612b, 612c, a beam length 618 and a beam mid-point 619, each beam being substantially straight along its first side 611a, 611b, 611c; each beam 610a, 610b, 610c of the beam array 613 comprised of a plurality of beam segments 620, 622, 624, each beam segment of the plurality of beam segments having a beam segment width 625a, 626a, 627a; 625b, 626b, 627b; 625c, 626c, 627c orthogonal to the beam length 618, each beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths 625a, 626a, 627a; 625b, 626b, 627b; 625c, 626c, 627c corresponding to each beam 610a, 610b, 610c vary along the beam length 618 based on a predetermined pattern; an included coupling beam 614 extending orthogonally across the beam array 613 to couple each beam 610a, 610b, 610c of the beam array 613 substantially at the corresponding beam mid-point 619; so that a heating of the beam array causes a beam array buckling and the coupling beam 614 to translate in a predetermined direction 648 generally normal to and outward from the second sides 612a, 612b, 612c of the array beams 610a, 610b, 610c.

In one embodiment, the predetermined pattern is characterized in that, along the beam length 618 from the first support 606 to the beam mid-point 619, beam segment widths 625a, 626a, 627a; 625b, 626b, 627b corresponding to successive beam segments 620, 622 do not decrease and at least sometimes increase, and along the beam length 618 from the beam mid-point 619 to the second support 608, beam segment widths 625b, 626b, 627b; 625c, 626c, 627c corresponding to successive beam segments 622, 624 do not increase and at least sometimes decrease.

In one embodiment, the heating of the beam array is provided by an included heater layer 628 disposed on the surface 604, the heater layer coupled to a heater layer input 638 and a heater layer output 640.

In another embodiment, each beam of the beam array is heated by a beam heater current 646a, 646b, 646c supplied by an included beam input 642 and beam output 644, thus forming the heating of the beam array.

In one embodiment, each beam of the beam array is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In another embodiment, each beam of the beam array is fabricated in a device layer of a silicon-on-insulator wafer.

As shown in FIG. 25, in one embodiment, each beam 610a, 610b, 610c of the beam array 613 comprises exactly three (3) beam segments 620, 622, 624.

In another embodiment, each beam of the beam array 613 comprises a plurality (n) of beam segments, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

As shown in FIG. 25, in one embodiment, the beam array 613 comprises exactly three (3) beams.

In another embodiment, the beam array 613 comprises a plurality (n) of beams, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

FIGS. 31-36 depict the thermal actuator 700 in greater detail.

Referring now to FIG. 31, there is shown an elevated top-down "birds-eye" view of the thermal actuator 700, including five (5) reference lines numbered 32-36.

As shown in FIGS. 31-36, the thermal actuator 700 comprises a substrate 702 having a surface 704; a first support 706 and a second support 708 disposed on the surface 704 and extending orthogonally therefrom; a beam 710 extending between the first support 706 and the second support 708, the beam 710 having a first side 711, a second side 712, a beam length 718 and a beam mid-point 719, the beam 710 being substantially straight along the second side 712; the beam comprised of a plurality of beam segments 720, 722, 724, each beam segment of the plurality of beam segments being having a beam segment width 725, 726, 727 orthogonal to the beam length 718, the beam 710 thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths 725, 726, 727 corresponding to the beam 710

vary along the beam length 718 based on a predetermined pattern; so that a heating of the beam 710 causes a beam buckling and the beam mid-point 719 to translate in a predetermined direction 748 generally normal to and outward from the second side 712.

As shown in FIG. 31, in one embodiment, the predetermined pattern is characterized in that, along the beam length 718 from the first support 706 to the beam mid-point 719, beam segment widths 725, 726 corresponding to successive beam segments 720, 722 do not increase and at least sometimes decrease, and along the beam length 718 from the beam mid-point 719 to the second support 708, beam segment widths 726, 727 corresponding to successive beam segments 722, 724 do not decrease and at least sometimes increase.

In one embodiment, the heating of the beam 710 is provided by an included heater layer 728 disposed on the surface 704, the heater layer coupled to a heater layer input 738 and a heater layer output 740.

In another embodiment, the heating of the beam 710 is provided by a beam heater current 746 supplied by an included beam input 742 and beam output 744.

In one embodiment, the beam is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In another embodiment, the beam is fabricated in a device layer of a silicon-on-insulator wafer.

As shown in FIG. 31, in one embodiment, the beam 710 comprises exactly three (3) beam segments 720, 722, 724.

In another embodiment, the beam 710 comprises a plurality (n) of beam segments, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

As shown, in one embodiment, the beam 710 comprises exclusively beam segments 720, 722, 724 having substantially parallel sides.

As shown, in one embodiment, the beam 710 comprises exactly two (2) beam segments 720, 724 that are substantially equal with respect to their corresponding beam segment lengths and beam segment widths 725, 727.

FIGS. 37-42 depict the thermal actuator 800 in greater detail.

Referring now to FIG. 37, there is shown an elevated top-down "birds-eye" view of the thermal actuator 800, including five (5) reference lines numbered 38-42.

As shown in FIGS. 37-42, the thermal actuator 800 comprises a substrate 802 having a surface 804; a first support 806 and a second support 808 disposed on the surface 804 and extending orthogonally therefrom; a plurality of beams 810a, 810b, 810c extending in parallel between the first support 806 and the second support 808, thus forming a beam array 813; each beam 810a, 810b, 810c of the beam array 813 having a first side 811a, 811b, 811c, a second side 812a, 812b, 812c, a beam length 818 and a beam mid-point 819, each beam being substantially straight along its second side 812a, 812b, 812c; each beam 810a, 810b, 810c of the beam array 813 comprised of a plurality of beam segments 820, 822, 824, each beam segment of the plurality of beam segments having a beam segment width 825a, 826a, 827a; 825b, 826b, 827b; 825c, 826c, 827c orthogonal to the beam length 818, each beam thus forming a corresponding plurality of beam segment widths; wherein the plurality of beam segment widths 825a, 826a, 827a; 825b, 826b, 827b; 825c, 826c, 827c corresponding to each beam 810a, 810b, 810c vary along the beam length 818 based on a predetermined pattern; an included coupling beam 814 extending orthogonally across the beam array 813 to couple each beam 810a, 810b, 810c of the beam array 813 substantially at the corresponding beam mid-point 819; so that a heating of the beam array causes a beam array buckling and the coupling beam 814 to translate in a predetermined direction 848 generally normal to and outward from the second sides 812a, 812b, 812c of the array beams 810a, 810b, 810c.

As shown in FIG. 37, in one embodiment, the predetermined pattern is characterized in that, along the beam length 818 from the first support 806 to the beam mid-point 819, beam segment widths 825a, 826a, 827a; 825b, 826b, 827b corresponding to successive beam segments 820, 822 do not increase and at least sometimes decrease, and along the beam length 818 from the beam mid-point 819 to the second support 808, beam segment widths 825b, 826b, 827b; 825c, 826c, 827c

corresponding to successive beam segments 822, 824 do not decrease and at least sometimes increase.

In one embodiment, the heating of the beam array is provided by an included heater layer 828 disposed on the surface 804, the heater layer coupled to a heater layer input 838 and a heater layer output 840.

In another embodiment, each beam of the beam array is heated by a beam heater current 846a, 846b, 846c supplied by an included beam input 842 and beam output 844, thus forming the heating of the beam array.

In one embodiment, each beam of the beam array is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In another embodiment, each beam of the beam array is fabricated in a device layer of a silicon-on-insulator wafer.

As shown in FIG. 37, in one embodiment, each beam 810a, 810b, 810c of the beam array 813 comprises exactly three (3) beam segments 820, 822, 824.

In another embodiment, each beam of the beam array 813 comprises a plurality (n) of beam segments, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

As shown in FIG. 37, in one embodiment, the beam array 813 comprises exactly three (3) beams.

In another embodiment, the beam array 813 comprises a plurality (n) of beams, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

FIGS. 43-48 depict the thermal actuator 900 in greater detail.

Referring now to FIG. 43, there is shown an elevated top-down "birds-eye" view of the thermal actuator 900, including five (5) reference lines numbered 44-48.

As shown in FIGS. 43-48, the thermal actuator 900 comprises a substrate 902 having a surface 904; a first support 906 and a second support 908 disposed on the surface 904 and extending orthogonally therefrom; a beam 910 extending between the first support 906 and the second support 908, the beam 910 having a first side 911, a second side 912, a beam length 918 and a beam mid-point 919, the beam 910 being

substantially straight along the first side 911; the beam comprised of a plurality of beam segments 920, 921, 922, 923, 924, each beam segment of the plurality of beam segments having a beam segment average width 925, 931, 926, 933, 927 orthogonal to the beam length 918, the beam 910 thus forming a corresponding plurality of beam segment average widths; wherein the plurality of beam segment average widths 925, 931, 926, 933, 927 corresponding to the beam 910 vary along the beam length 918 based on a predetermined pattern; so that a heating of the beam 910 causes a beam buckling and the beam mid-point 919 to translate in a predetermined direction 948 generally normal to and outward from the second side 912.

As shown in FIG. 43, in one embodiment, the predetermined pattern is characterized in that, along the beam length 918 from the first support 906 to the beam mid-point 919, beam segment average widths 925, 931, 926 corresponding to successive beam segments 920, 921, 922 do not decrease and at least sometimes increase, and along the beam length 918 from the beam mid-point 919 to the second support 908, beam segment average widths 926, 933, 927 corresponding to successive beam segments 922, 923, 924 do not increase and at least sometimes decrease.

Still referring to FIG. 43, it will be understood that the predetermined pattern of beam segment average widths 925, 931, 926, 933, 927 depicted therein corresponds to a first beam moment 956 and a second beam moment 958, as shown.

In one embodiment, the heating of the beam 910 is provided by an included heater layer 928 disposed on the surface 904, the heater layer coupled to a heater layer input 938 and a heater layer output 940.

In another embodiment, the heating of the beam 910 is provided by a beam heater current 946 supplied by an included beam input 942 and beam output 944.

In one embodiment, the beam is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In another embodiment, the beam is fabricated in a device layer of a silicon-on-insulator wafer.

As shown in FIG. 43, in one embodiment, the beam 910 comprises exactly five (5) beam segments 920, 921, 922, 923, 924.

In another embodiment, the beam 910 comprises a plurality (n) of beam segments, where n does not equal 5. In this embodiment, for example, n equals 2, 3, 4, 6, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

As shown, in one embodiment, the beam 910 comprises exactly three (3) beam segments 920, 922, 924 having substantially parallel sides.

As shown, in one embodiment, the beam 910 comprises exactly two (2) beam segments 920, 924 that are substantially equal with respect to their corresponding beam segment lengths and beam segment widths 925, 927.

FIGS. 49-54 depict the thermal actuator 1000 in greater detail.

Referring now to FIG. 49, there is shown an elevated top-down "birds-eye" view of the thermal actuator 1000, including five (5) reference lines numbered 50-54.

As shown in FIGS. 49-54, the thermal actuator 1000 comprises a substrate 1002 having a surface 1004; a first support 1006 and a second support 1008 disposed on the surface 1004 and extending orthogonally therefrom; a plurality of beams 1010a, 1010b, 1010c extending in parallel between the first support 1006 and the second support 1008, thus forming a beam array 1009; each beam 1010a, 1010b, 1010c of the beam array 1009 having a first side 1011a, 1011b, 1011c, a second side 1012a, 1012b, 1012c, a beam length 1018 and a beam mid-point 1019, each beam being substantially straight along its first side 1011a, 1011b, 1011c; each beam 1010a, 1010b, 1010c of the beam array 1009 comprised of a plurality of beam segments 1020, 1021, 1022, 1023, 1024, each beam segment of the plurality of beam segments having a beam segment average width 1025a, 1031a, 1026a, 1033a, 1027a; 1025b, 1031b, 1026b, 1033b, 1027b; 1025c, 1031c, 1026c, 1033c, 1027c orthogonal to the beam length 1018, each beam thus forming a corresponding plurality of beam segment average widths; wherein the plurality of beam segment average widths 1025a, 1031a, 1026a, 1033a, 1027a; 1025b, 1031b, 1026b, 1033b, 1027b; 1025c, 1031c, 1026c, 1033c, 1027c corresponding to each beam 1010a, 1010b, 1010c vary along the beam length 1018 based on a predetermined pattern; an included coupling beam 1005 extending orthogonally across the beam array 1009 to couple each beam 1010a, 1010b, 1010c of the beam array 1009 substantially at the corresponding beam mid-

point 1019; so that a heating of the beam array causes a beam array buckling and the coupling beam 1014 to translate in a predetermined direction 1048 generally normal to and outward from the second sides 1012a, 1012b, 1012c of the array beams 1010a, 1010b, 1010c.

As shown in FIG. 49, in one embodiment, the predetermined pattern is characterized in that, along the beam length 1018 from the first support 1006 to the beam mid-point 1019, beam segment average widths 1025a, 1031a, 1026a; 1025b, 1031b, 1026b; 1025c, 1031c, 1026c corresponding to successive beam segments 1020, 1021, 1022 do not decrease and at least sometimes increase, and along the beam length 1018 from the beam mid-point 1019 to the second support 1008, beam segment widths 1026a, 1033a, 1027a; 1026b, 1033b, 1027b; 1026c, 1033c, 1027c corresponding to successive beam segments 1022, 1023, 1024 do not increase and at least sometimes decrease.

Still referring to FIG. 49, it will be understood that the predetermined pattern of beam segment average widths 1025a, 1031a, 1026a, 1033a, 1027a; 1025b, 1031b, 1026b, 1033b, 1027b; 1025c, 1031c, 1026c, 1033c, 1027c depicted therein corresponds to a plurality of first beam moments 1056a, 1056b, 1056c and second beam moments 1058a, 1058b, 1058c, as shown.

In one embodiment, the heating of the beam array 1009 is provided by an included heater layer 1028 disposed on the surface 1004, the heater layer coupled to a heater layer input 1038 and a heater layer output 1040.

In another embodiment, each beam of the beam array 1009 is heated by a beam heater current 1046a, 1046b, 1046c supplied by an included beam input 1042 and beam output 1044, thus forming the heating of the beam array.

In one embodiment, each beam of the beam array is fabricated of a low-conductivity material of either monocrystalline silicon or polycrystalline silicon.

In another embodiment, each beam of the beam array is fabricated in a device layer of a silicon-on-insulator wafer.

As shown in FIG. 49, in one embodiment, beam 1010a, 1010b, 1010c of the beam array 1009 comprises exactly five (5) beam segments 1020, 1021, 1022, 1023, 1024.

In another embodiment, each beam of the beam array 1009 comprises a plurality (n) of beam segments, where n does not equal 5. In this embodiment, for example, n equals 2, 3, 4, 6, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

As shown in FIG. 49, in one embodiment, the beam array 1009 comprises exactly three (3) beams.

In another embodiment, the beam array 1009 comprises a plurality (n) of beams, where n does not equal 3. In this embodiment, for example, n equals 2, 4, 5, 12, 15, 32, 82, 109, 188, 519, 1003, etc.

The table below lists the drawing element reference numbers together with their corresponding written description:

Number:	Description:
100a	optical waveguide switch comprising the thermal actuator 200
100b	optical waveguide switch comprising the thermal actuator 300
100c	optical waveguide switch comprising the thermal actuator 400
100d	optical waveguide switch comprising the thermal actuator 500
100e	optical waveguide switch comprising the thermal actuator 600
100f	optical waveguide switch comprising the thermal actuator 700
100g	optical waveguide switch comprising the thermal actuator 800
100h	optical waveguide switch comprising the thermal actuator 900
100i	optical waveguide switch comprising the thermal actuator 1000
200	first embodiment of a thermal actuator
202	substrate
204	surface of the substrate 202
206	first support
208	second support
210	support spacing
212a-212d	plurality of beams
214	beam array
216	first beam of the beam array 214
218	last beam of the beam array 214
220	coupling beam

222	pair of adjacent beams in the beam array 214
224	beam spacing
226	beam width
228	heater layer
230	device layer
232	silicon-on-insulator wafer
234	buried oxide layer
236	beam temperature
238	heater layer input
240	heater layer output
242	beam input
244	beam output
246	beam heater current
248	predetermined direction
250	one side of the beam array 214
252	opposite side of the beam array 214
254	beam heating parameter
256	beam temperature distribution of the beam array 214
300	second embodiment of a thermal actuator
302	substrate
304	surface of the substrate 302
306	first support
308	second support
310	support spacing
312a-312e	plurality of beams
314	beam array
316	first beam of the beam array 314
318	last beam of the beam array 314
320	coupling beam
322	pair of adjacent beams in the beam array 314
324	beam spacing

326	beam width
328	heater layer
330	device layer
332	silicon-on-insulator wafer
334	buried oxide layer
336	beam resistance
338	heater layer input
340	heater layer output
342	beam input
344	beam output
346	beam heater current
348	predetermined direction
350	one side of the beam array 314
352	opposite side of the beam array 314
354	beam heating parameter
400	third embodiment of a thermal actuator
402	substrate
404	surface of the substrate 402
406	first support
408	second support
410	support spacing
412a-412e	plurality of beams
414	beam array
416	first beam of the beam array 414
418	last beam of the beam array 414
420	coupling beam
422	pair of adjacent beams in the beam array 414
424	beam spacing
426	beam width
428	heater layer
430	device layer

432	silicon-on-insulator wafer
434	buried oxide layer
436	beam resistance
438	heater layer input
440	heater layer output
442	beam input
444	beam output
446	beam heater current
448	predetermined direction
450	one side of the beam array 414
452	opposite side of the beam array 414
454	beam heating parameter
500	fourth embodiment of a thermal actuator
502	substrate
504	surface
506	first support
508	second support
510	beam
511	first beam side
512	second beam side
515	first beam segment neutral axis
516	second beam segment neutral axis
517	third beam segment neutral axis
518	beam length
519	beam mid-point
520	first beam segment
522	second beam segment
524	third beam segment
525	first beam segment width
526	second beam segment width
527	third beam segment width

528	heater layer
530	device layer
532	handle wafer
534	buried oxide layer
538	substrate heater electrical input
540	substrate heater electrical output
542	beam heater electrical input
544	beam heater electrical output
546	beam heater current
548	predetermined direction
554	offset between first beam segment neutral axis 515 and second beam segment neutral axis 516
556	first beam moment
557	offset between second beam segment neutral axis 516 and third beam segment neutral axis 517
558	second beam moment
600	fifth embodiment of a thermal actuator
602	substrate
604	surface
606	first support
608	second support
610a-610c	plurality of beams
611a-611c	first beam side
612a-612c	second beam side
613	beam array
614	coupling beam
615a-615c	first beam segment neutral axis
616a-616c	second beam segment neutral axis
617a-617c	third beam segment neutral axis
618	beam length
619	beam mid-point

620	first beam segment
622	second beam segment
624	third beam segment
625a-625c	first beam segment width
626a-626c	second beam segment width
627a-627c	third beam segment width
628	heater layer
630	device layer
632	handle wafer
634	buried oxide layer
638	substrate heater electrical input
640	substrate heater electrical output
642	beam heater electrical input
644	beam heater electrical output
646a-646c	beam heater current
648	predetermined direction
654a-654c	offset between first beam segment neutral axis 615a-615c and second beam segment neutral axis 616a-616c
656a-656c	first beam moment
657a-657c	offset between second beam segment neutral axis 616a-616c and third beam segment neutral axis 617a-617c
658a-658c	second beam moment
700	sixth embodiment of a thermal actuator
702	substrate
704	surface
706	first support
708	second support
710	beam
711	first beam side
712	second beam side
715	first beam segment neutral axis

716	second beam segment neutral axis
717	third beam segment neutral axis
718	beam length
719	beam mid-point
720	first beam segment
722	second beam segment
724	third beam segment
725	first beam segment width
726	second beam segment width
727	third beam segment width
728	heater layer
730	device layer
732	handle wafer
734	buried oxide layer
738	substrate heater electrical input
740	substrate heater electrical output
742	beam heater electrical input
744	beam heater electrical output
746	beam heater current
748	predetermined direction
754	offset between first beam segment neutral axis 715 and second beam segment neutral axis 716
756	first beam moment
757	offset between second beam segment neutral axis 716 and third beam segment neutral axis 717
758	second beam moment
800	seventh embodiment of a thermal actuator
802	substrate
804	surface
806	first support
808	second support

810a-810c	plurality of beams
811a-811c	first beam side
812a-812c	second beam side
813	beam array
814	coupling beam
815a-815c	first beam segment neutral axis
816a-816c	second beam segment neutral axis
817a-817c	third beam segment neutral axis
818	beam length
819	beam mid-point
820	first beam segment
822	second beam segment
824	third beam segment
825a-825c	first beam segment width
826a-826c	second beam segment width
827a-827c	third beam segment width
828	heater layer
830	device layer
832	handle wafer
834	buried oxide layer
838	substrate heater electrical input
840	substrate heater electrical output
842	beam heater electrical input
844	beam heater electrical output
846a-846c	beam heater current
848	predetermined direction
854a-854c	offset between first beam segment neutral axis 815a-815c and second beam segment neutral axis 816a-816c
856a-856c	first beam moment
857a-857c	offset between second beam segment neutral axis 816a-816c and third beam segment neutral axis 817a-817c

858a-858c	second beam moment
900	eighth embodiment of a thermal actuator
902	substrate
904	surface
906	first support
908	second support
910	beam
911	first beam side
912	second beam side
913	first beam segment neutral axis
914	second beam segment neutral axis
915	third beam segment neutral axis
916	fourth beam segment neutral axis
917	fifth beam segment neutral axis
918	beam length
919	beam mid-point
920	first beam segment
921	second beam segment
922	third beam segment
923	fourth beam segment
924	fifth beam segment
925	first beam segment average width
926	third beam segment average width
927	fifth beam segment average width
928	heater layer
930	device layer
931	second beam segment average width
932	substrate
933	fourth beam segment average width
934	buried oxide layer
938	substrate heater electrical input

940	substrate heater electrical output
942	beam heater electrical input
944	beam heater electrical output
946	beam heater current
948	predetermined direction
954	offset between first beam segment neutral axis 913 and third beam segment neutral axis 915
956	first beam moment
957	offset between third beam segment neutral axis 915 and fifth beam segment neutral axis 917
958	second beam moment
1000	ninth embodiment of a thermal actuator
1002	substrate
1004	surface
1005	coupling beam
1006	first support
1008	second support
1009	beam array
1010a-1010c	plurality of beams
1011a-1011c	first beam side
1012a-1012c	second beam side
1013a-1013c	first beam segment neutral axis
1014a-1014c	second beam segment neutral axis
1015a-1015c	third beam segment neutral axis
1016a-1016c	fourth beam segment neutral axis
1017a-1017c	fifth beam segment neutral axis
1018	beam length
1019	beam mid-point
1020	first beam segment
1021	second beam segment
1022	third beam segment

1023	fourth beam segment
1024	fifth beam segment
1025a-1025c	first beam segment average width
1026a-1026c	third beam segment average width
1027a-1027c	fifth beam segment average width
1028	heater layer
1030	device layer
1031a-1031c	second beam segment average width
1032	substrate
1033a-1033c	fourth beam segment average width
1034	buried oxide layer
1038	substrate heater electrical input
1040	substrate heater electrical output
1042	beam heater electrical input
1044	beam heater electrical output
1046a-1046c	beam heater current
1048	predetermined direction
1054a-1054c	offset between first beam segment neutral axis 1013a-1013c and third beam segment neutral axis 1015a-1015c
1056a-1056c	first beam moment
1057a-1057c	offset between third beam segment neutral axis 1015a-1015c and fifth beam segment neutral axis 1017a-1017c
1058a-1058c	second beam moment

While various embodiments of a thermal actuator and an optical waveguide switch including the same, in accordance with the present invention, have been described hereinabove, the scope of the invention is defined by the following claims.